Plasma Science in Planetary Entry

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I. Introduction

Spacecraft entering a planetary atmosphere dissipate a great deal of energy into the surrounding gas. In the frame of reference of the vehicle, the atmospheric gas suddenly decelerates from hypersonic (Mach ~5-50) to subsonic velocities. The kinetic energy of the gas is rapidly converted to thermal and chemical energy, forming a bow shock behind which a plasma with energies on the order of one electron volt (eV) is produced. The resulting shock layer relaxes from strong thermal non-equilibrium that is translationally hot but internally cold and un-ionized toward a thermochemically equilibrated plasma over a distance of a few centimeters. Composition is dependent upon the planetary atmosphere – Air for Earth, CO_2/N_2 for Mars and Venus, N_2/CH_4 for Titan and $H_2/He/CH_4$ for Saturn, Neptune and Jupiter. Typical velocities of entry may range from 3-7 km/s (4-25 MJ/kg) for Titan/Mars, 8-14 km/s (30-100 MJ/kg) for Earth/Venus, and 25-40 km/s (300-800 MJ/kg) for outer planets. The equilibrium plasmas produced from these conditions are highly dissociated (up to and above 99%) and ionized (0.1-15%), with temperatures from 7,000-15,000K and pressures from 0.1-1.0 bar. Understanding the behavior of these plasmas – the way in which they approach equilibrium, how they radiate, and how they interact with materials – is an active area of research necessitated by requirements to predict and test the performance of thermal protection systems (TPS) that enable spacecraft to deliver scientific instruments, and people, to foreign worlds and back to Earth. The endeavor is a multi-physics problem, with key processes highlighted in Fig. 1. This white paper describes the current state of the art in simulating shock layer plasmas both computationally and in ground test facilities. Gaps requiring further research and development are identified.

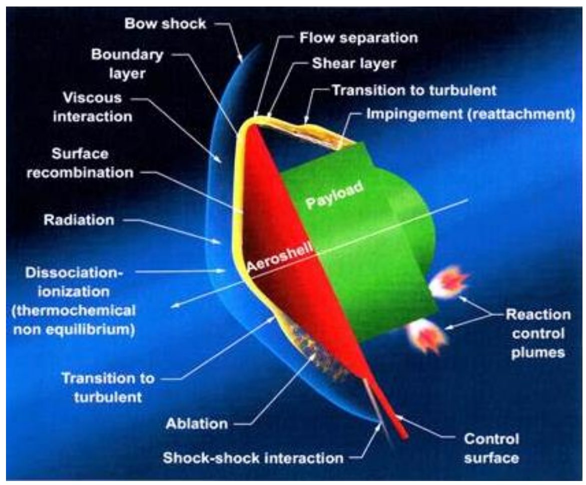

Figure 1. The multi-physics nature of entry flowfield/plasmas. [AIAA-2007-4263].

II. Facilities and Diagnostics

The conditions of planetary entry are extreme enough that it is not possible to produce a test that simulates all aspects of the entry environment in a laboratory experiment. There are two types of facilities that can match some aspects of the high enthalpy plasma flow described here: impulse facilities (e.g. shock tubes) and steady high enthalpy sources (e.g. arc-jets).

The shock tube or tunnel produces a high-velocity flow by rupturing a diaphragm between high and low-pressure gas regions. One method is to use an arc discharge in the high-pressure region to raise the gas temperature (hence sonic velocity), allowing shock waves to reach speeds up to Mach 50. There are two primary applications of the shock tube in entry research. By matching the gas composition and density in the low-pressure region to a planetary atmosphere and the shock velocity to the vehicle velocity, similarity is obtained to the stagnation line of an entry vehicle bow shock. This shock wave plasma is then measured to probe reaction kinetics, thermal non-equilibrium relaxation processes, ionization and radiation. These processes must be characterized to build, verify, and validate models of planetary entry. Emission from the plasma can be sufficiently intense to radiatively heat the spacecraft. Plasma emission is measured within the shock tube by imaging spectrometers with wavelength ranges spanning the vacuum ultraviolet (120 nm) to mid-infrared (5.5 μm). Emission spectroscopy data is analyzed in terms of absolute radiative magnitude, rotational/vibrational/electronic temperatures, degree of ionization, and species number densities. It is desired to more accurately measure densities and temperatures of electrons and atoms/molecules in ground and excited states by developing and applying non-intrusive techniques capable of measuring these properties with high temporal resolution. The second application of shock tubes is to produce and expand a high-enthalpy flow around a test article. This creates a bow shock, which may be analyzed for the same properties, while measuring heat flux and pressure at the test article surface. This type of study is often used for testing fluid mechanic and aeroheating phenomena and is less dependent upon plasma properties.

While the shock tube may produce flow with similarity in chemical composition, energy partitioning, and radiation, they are short-duration processes that are unable to test how a TPS material responds to the plasma and its capacity to survive entry conditions. For this purpose, relatively long-duration plasma-based facilities are employed. Among these facilities are high-powered inductively coupled plasmas, inductive/microwave plasma torches, and arc-heated flows. The largest class of arc-heated flows, known as arc-jets, utilize constricted arcs with powers up to 150 MW. Atmospheric mixtures are fed through the arc flow at rates of ~1 kg/s and pressures of ~8 bar, obtaining high temperatures/enthalpy before expanding the plasma through a nozzle. The expanded flow impinges on test articles at supersonic speeds, establishing a shock-heated plasma around the test article for durations of up to several minutes. Arc-jets are generally able to achieve flight-like similarity in terms of one or two important parameters (e.g. heat flux, shear or pressure). Recent development in arc-jets includes the application of high-powered (4 x 50 kW) fiber-coupled lasers to simultaneously heat the samples convectively and radiatively. Techniques such as laser-induced fluorescence, and absorption and emission spectroscopy have been employed to assess degree of dissociation, temperatures, and mixing profiles. Better characterization of arc-jet flows is desired to provide a more accurate representation of the thermochemical state of the heating environment.

III. Plasma Modeling for Entry

As discussed above, it is not possible to fully reproduce entry plasmas in the laboratory. Thus, spacecraft design and engineering demand that entry environments be accurately predicted using physics-based models which extrapolate the ground test data to a flight-relevant condition.

Computational Fluid Dynamics (CFD) is employed to predict flow field properties. Due to the computational expense of simulating flight-scale hypersonic flows with strong shocks and thin boundary layers, simplified plasma models are required. The usual approach is to model the plasma with separate total energy and electron-electronic-vibrational energy equations. This reduces the problem to two temperatures: translational-rotational (T_{tr}) and vibro-electronic (T_{ve}). Electric field equations are simplified assuming ambipolar diffusion and quasi-neutrality, so that the current flux may be replaced with an electron pressure gradient. Landau-Teller relaxation describes energy transfer between translational and vibrational modes. Two-temperature reaction kinetics are handled phenomenologically. While electron impact-driven reactions may be assumed to depend on T_e, the controlling temperature for heavy particle dissociation is typically approximated as $\sqrt{T_t T_v}$. Current areas of research include using state-specific rates (typically based on theoretical calculations) to model vibrationally and electronically specific processes that may yield more rigorous temperature and energy dependencies.

To predict emission spectra, and hence radiative heating, it is necessary to model electronic state-specific processes. CFD provides distributions of total temperature and species number densities as input. The radiation solver formulates mole balances on all electronic states of a species and applies a quasi-steady state approximation to excited levels to obtain electronic populations which then determine radiative magnitude. Parameters that go into these master equations include state-to-state excitation rates by electrons and heavy particles, radiative lifetimes to derive spontaneous and stimulated emission and absorption, and state-specific rates for ionization and/or dissociation from each excited electronic state. Whether from experiment or theory, fundamental data to accurately formulate these model parameters are limited, and many of the rates must be extrapolated or estimated based on what is known for the ground state.

The ultimate motivation of all these studies is to predict the heat transfer to the vehicle surface, which is then coupled to a material response model that predicts the material temperature profile, in-depth chemistry (pyrolysis) and surface material erosion (recession). The interaction of the shock plasma with the spacecraft TPS is an important consideration for these predictions. Material response models are typically tuned to material performance data (temperature profiles and recession) obtained via arc-jet facilities. Ground-to-flight traceability, or the translation of a model based on an environment that differs from flight, is an open concern. Current areas of investigation are catalytic reactions of the boundary layer gas with the surface, and radiative absorption and emission from ablated TPS material in the boundary layer. Few studies model the plasma sheath, assuming electrons/ions to recombine in the cold boundary layer. Synergistic effects between radiation, charged species and chemical reactions on erosion are not considered.

IV. Progress in Planetary Entry Simulation

Facilities

Modeling of test facilities used for entry technology development remains a grand challenge. Within shock tubes, the fast kinetics and relatively slow flow time scales create very stiff computational fluid dynamics problems. To accurately model the boundary layer and the shock front requires cell resolutions on the order of microns, while the facility scale is several meters. The large disparity in the spatial and temporal scales of these physical mechanisms, which must be modeled, require the development and use of advanced numerical methods in order to make the simulation computational feasible.

The ability to model an arc-jet within the nozzle and test chamber is now fairly well developed. Modeling the arc column, which provides the upstream boundary condition for flow through the nozzle, remains an active area of development. The high pressure and low speeds in the chambers upstream of the converging/diverging nozzle is accurately modeled by the magneto-hydrodynamic (MHD) approximation assuming chemical equilibrium but variable composition gas. Models for the plasma sheath transition are required to properly model arc attachment at the electrodes, but the development of simplified models of the arc attachment mechanisms remain a challenge. Cool, electrically-floating walls confine the plasma to the core region of the flow, making the arc unstable; three-dimensional simulations are necessary to accurately capture these instabilities. Radiative transport from the hot arc core region to the walls and the cool plasma near the wall, combined with the highly three-dimensional arc core, requires tight coupling between the radiative transfer and MHD equations. The wide temperature range between the core and the walls requires accurate representation of opacities.

Quantum Mechanics

The state-specific equations used in entry modeling require a full set of parameters for atoms, molecules, ions and electron interactions. Quantum mechanical computation provides a viable means to define parameters that are not available experimentally. The electronic wavefunctions for most molecules and molecular ions can be calculated using commercial software, while fully parallel quantum chemistry software for CASSCF and MRCI calculations is being developed by NASA for more demanding applications.

For heavy particle collisions, the electronic Schrodinger equation is solved for many fixed geometric arrangements of the constituent atoms to generate a potential energy surface (PES). This PES is used as input for quantum or classical scattering calculations to determine collision cross sections (or rate coefficients) for molecular dissociation, exchange reactions, and ro-vibrationally inelastic processes. Charge interactions studied by quantum mechanics include electron-impact ionization/excitation and dissociative recombination (e.g. $N_2^+ + e^- \leftrightarrow N + N$). The electron-impact ionization cross section is determined by a binary-encounter interaction between the incoming electron, the bound electrons, and the dipole interaction between the incoming electron and the dipole field of the target. Cross sections have been successfully computed for several atoms and molecules. For electron-impact excitation of atoms/molecules, a perturbation treatment is used. Dissociative recombination includes both electron scattering dynamics and nuclear dynamics leading to dissociation. Calculation of this process combines the finite-element Z-matrix code to determine the width of the compound state, accurate calculations of potential curves for nuclear motions, and time-dependent wave packet calculation of the dissociation recombination cross section. While the work is ongoing, there are numerous parameters which remain unknown.

Applied Modeling

Comparisons of shock tube data to simulations with radiation solvers are used for two purposes: to inform design margins for vehicle thermal protection systems and to improve models where significant discrepancies are identified. An example of the former is the quantification of the disagreement in radiation measured in Martian and Air gas mixtures in equilibrium and non-equilibrium regimes, which is then propagated through radiative transport equations to inform design margins for NASA's Mars 2020 and Orion missions. For the latter purpose, recent studies have led to new proposed reaction rates for CO and NO dissociation and exchange rates, among other improvements. The new rates inferred from shock tube emission data are generally within the scatter of published rates in the literature. In general, the non-equilibrium and equilibrium radiation encountered during Earth and Mars entry is well-validated. Some outstanding problems include correctly simulating CO 4th Positive emission for Mars, non-equilibrium molecular radiation in Air, and radiation from expanding flow environments. The latter is of particular interest for the backshell of blunt entry capsules where the flow expanding behind the vehicle has historically been assumed to be non-radiating, yet recent predictions suggest radiation to be the dominant heating mechanism. Radiation in other entry atmospheres (Titan, Gas Giants, Venus) is less validated and subject to further study.

Plasma physics modeling techniques developed originally for planetary entry simulations have recently been leveraged for the more extreme problem of meteor entries. The motivation for meteor simulations may be separated into two categories. The first is the prediction of heating in order to determine the mass loss or ablation rate of the meteor, which is important to assess the impact threat of a given meteor. Challenging aspects of these simulations are the importance of coupling between the radiative energy and the flow field, where the radiative emission from the shock layer gas cools the shock layer, and the strong radiative absorption by ablation products, which can reduce incident heating by over an order-of-magnitude. The second motivation for meteor simulations is the prediction of the radiative flux emitted from the meteor shock layer and wake: This may result in a life-threatening heat flux to the ground for large meteor events (such as Tunguska), or a detectable light signal to an observation device for smaller events. The radiative flux from a meteor is sensitive to non-equilibrium chemistry in the wake. Non-equilibrium processes such as radiative recombination may have a significant impact on the level of ionization. Non-equilibrium modeling of metallic and oxide ablation products not encountered in planetary entry simulations is also required.

V. Concluding Remark

The application of plasma physics phenomena to entry environments is an active area of research motivated and supported primarily by NASA. While much of the work is conducted in-house at NASA Field Centers, there are significant contributions from academic partners through the use of co-operative agreements and grants. Similar work is also conducted by international space agencies such as JAXA and ESA, and overlap exists with Department of Defense interests in hypersonic non-equilibrium flows and material interactions. Much of the work in this area is reported in the Thermophysics section of the American Institute of Aeronautics and Astronautics. Studies of entry plasma physics have led to advancements in quantum mechanics, numerical methods, plasma diagnostics, meteor entry physics and damage, and high-temperature thermodynamics and reaction kinetics. This has, in turn, led to significant improvements in the design and engineering of entry vehicles. Areas of research requiring further study include, but are not limited to, improvements in diagnostics of entry plasma flows, high energy plasma facilities for reproducing entry conditions, multi-physics modeling and simulation for arc heaters and shock tubes, simulation of coupled radiative (non-adiabatic) flows and material interaction, heating augmentation and material erosion from particles within entry plasmas (i.e. dusty flows), and measurement and prediction of energetic exchange and reaction mechanisms through, e.g. crossed-beam experiments and computational chemistry.